The Operation of Diesel Gensets in a CERTS Microgrid

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***Abstract*— In this paper the operation of diesel engine-driven wound-field synchronous generator sets as Distributed Generators (DG's) is studied. The objective of this work is to develop the modeling and control framework for such gensets to enable their operation in a distribution system that contains multiple DG's including inverter-based sources. The paper presents experimental results for the interaction of conventional gensets with inverter-based sources in a microgrid test system. From the test results it is observed that there is significant circulating reactive power between the sources as well as frequency oscillations caused by the response of the conventional genset controller. A new controller for the genset is proposed that alleviates these issues and enables the various sources to share power and maintain power quality within the system. The operation of the new controller is demonstrated using simulation results.**

***Index Terms*—Power generation control, AC generator excitation, microgrid, DER.**

I. INTRODUCTION TO MICROGRID POWER SYSTEMS

The Microgrid concept presented by CERTS [1]-[3] is an advanced approach for enabling integration of, in principle, an unlimited quantity of distributed resources into the electricity grid in a cost-effective manner.

The CERTS Microgrid [3] (henceforth referred to as the microgrid) refers to a collection of sensitive loads and sources connected to the utility via a static switch as shown in Fig. 1. The sources in the microgrid are distributed generators that can be locally dispatched and controlled. The goal of the microgrid is to improve the quality of power experienced by the load and to improve the reliability of the supply. To the utility, the microgrid appears as a single controllable supply that responds dynamically to changes in the transmission and distribution system.

The major features of the CERTS Microgrid are [3], [4]:

1. Peer-to-peer environment
2. No explicit communications system
3. Plug-and-play
4. Scalable system
5. CHP to improve efficiency
6. Smooth transfer between island and grid-connected operation

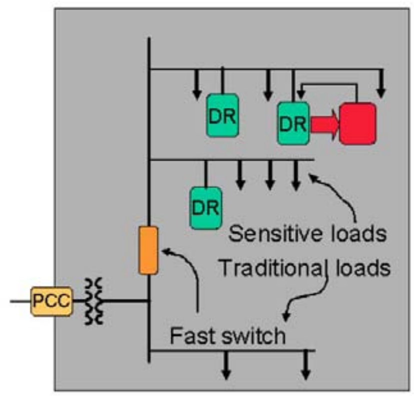

Fig. 1. Typical structure of a Microgrid power system

The microgrid has two principal components, the static switch and the microsource. The static switch has the ability to autonomously island the microgrid from disturbances such as faults, IEEE 1547 events, or power quality events. After islanding, the reconnection of the microgrid is achieved autonomously after the tripping event is no longer present. This synchronization is achieved by using the frequency difference between the islanded microgrid and the utility grid. Each microsource can seamlessly balance the power on the islanded microgrid using real power vs. frequency droop and maintain voltage using the reactive power vs. voltage droop (Fig. 2).

In a microgrid there is no "master" controller or source. Each of the sources is connected in a peer-to-peer fashion and a decentralized control scheme is implemented. This arrangement increases the reliability of the system in comparison to having a master-slave or centralized control scheme. In the case of a master-slave controller architecture [5,6], the failure of the master controller would compromise the operation of the entire system.

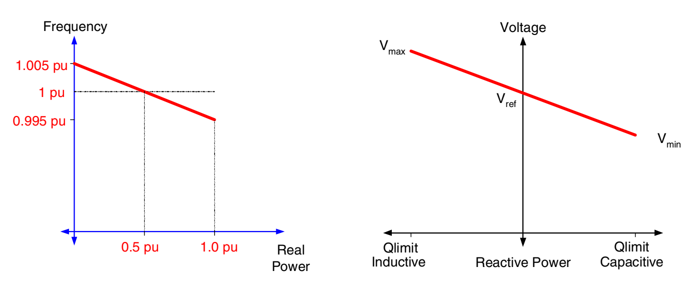

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Fig. 2. Real and reactive power droop curves for DG sources in a microgrid

Decentralized control in the microgrid is achieved without an explicit communications system by using real and reactive power droop-based local controllers. A communications system can be set up to vary the DG set points to improve efficiency or to decrease the overall cost of operation. However this communications network is not needed for the dynamic operation of the system. Since the presence of a communications network is not critical, the introduction of new resources into the microgrid can be achieved quite easily. This plug-and-play approach makes it possible to conveniently expand the microgrid and to scale it to meet the customer requirements.

II. Microgrid Prime movers and Paper Objective

Sources such as natural gas-based microturbines, fuel cells, PV panels, wind turbines use a power electronics interface on the front end to provide the necessary AC voltage at the utility frequency (50Hz or 60Hz). The inverter is typically a voltage-source converter that provides the necessary control of the bus voltage phase and magnitude. Electrical energy storage can be added to the DC bus to decouple the dynamics of the prime mover from the output [7]. Sources such as fuel cells and PV panels produce DC directly and only an inverter is needed to produce AC output at the desired voltage and frequency.

A diesel genset consists of an internal combustion (IC) engine and a synchronous generator coupled on the same shaft. Such systems are widely used as backup or emergency power in commercial as well as industrial installations. Diesel gensets are also heavily used in remote locations where it is impractical or prohibitively expensive to connect to utility power. Diesel gensets used in prime and continuous power applications are typically designed to operate at higher efficiencies since, in the long run, the fuel costs will dominate the initial capital costs.

The generator in the genset is typically either a permanent magnet or a wound-field synchronous machine. In the case of a permanent magnet generator, the front end consists of a rectifier and a voltage-source converter to provide the necessary AC voltage at the desired frequency [8]. The presence of a power electronics front end increases the overall cost of the system and decreases its fault tolerance. However, the presence of the inverter enables non-synchronous operation of the engine which makes it possible to achieve increased power density and higher efficiency [8].

Machines with wound-field generators require an exciter and a voltage regulator to control the AC voltage produced by the machine. No inverter is needed since the machine provides the AC voltage at the desired frequency provided that the speed of the shaft is held close to the required fixed value. The reduced cost of the system due to the absence of the power electronics front end is one of its major advantages. However, a significant drawback of this system is that without the inverter front end, the dynamics of the prime mover cannot be decoupled from the output of the generator.

The objective of this paper is to investigate the integration of diesel gensets into microgrids that can also include sources with power electronics front ends. Both modeling and controls issues are addressed that explain the behavior of conventional diesel gensets in a microgrid as well as modifications that improve their performance. Simulation and experimental results are provided to confirm key analytical results.

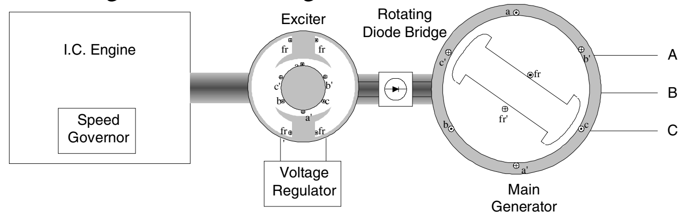

Fig. 3. Typical structure of a diesel genset.

III. Modeling of IC Engine Based Genset Systems

In a distribution system that contains different sources, the response of the engine-based synchronous machine will be slower in comparison to those sources that have power electronic inverters. Hence, an engine model is required that quantifies the major delays and relates the input fuel command to the average torque produced on the shaft.

A. *Mean effective pressure based model for IC engine*

The simplified modeling of IC engine gensets for simulation in power system applications has been carried out in [9]-[11]. Detailed modeling of the mechanical governor used in small engine systems has been reported in [12] and this model has been used in this paper in conjunction with the engine model.

The key feature of the engine model is the use of a pure time delay to represent the time it takes for a fuel command to result in torque applied to the shaft. The value of this time delay depends on the shaft rotational speed and the number of active cylinders in the engine. The relationship between steady-state fuel input and engine torque output can be obtained from the torque fuel map. The speed operating range of synchronous gensets is typically narrow and the friction losses can be assumed to be proportional to speed.

B. *Modeling of synchronous machine*

The equations used to model the synchronous machine electrical dynamic characteristics are well known and can be obtained from the following sources [13], [14]. In conventional power system models, the torque angle of the machine δ is used to convert the stator synchronous frame voltages into the rotor reference frame. The angle δ is calculated using the swing equation and the assumption that the steady-state frequency in the system is always a constant (either 50Hz or 60Hz). This assumption makes it possible to calculate the slip speed and, hence, the value of the torque angle as a function of time.

In contrast, the reference frequency in a microgrid application is not fixed. In steady-state, the frequency depends on the magnitude of the load and the power frequency curves of the sources. Hence, the calculation of the torque

Fig. 4. Diesel genset installed at UW-Madison

angle for a machine requires knowledge of the system load and generation. One of the key goals of the microgrid system is to operate the system without any communications system and to utilize only local information in the control of a distributed generation resource. To achieve this goal, a position sensor such as an encoder or resolver can be mounted on the shaft of the genset. The rotor position can then be used to directly convert the terminal voltages from the stationary reference frame to the rotating rotor reference frame.

C. Modeling of brushless exciter

The brushless exciter is an inverted synchronous machine with a DC stator winding and AC windings on the rotor. In larger generators the rotor windings are typically three-phase [15]. In smaller machines (typically less than 50kW rating) the windings are typically single-phase to reduce cost. The AC voltage is rectified into DC using a diode bridge that is integrated into the rotor shaft. Hence, the main field voltage can be controlled by adjusting the input voltage to the brushless exciter.

The rating of the brushless exciter in gensets is typically 10% of the rating of the main generator, and these machines typically operate unsaturated [16,17]. The entire exciter with diode bridge can be modeled as a first-order transfer function for small machines [17]-[19] with a lower and upper limit.

D. Diesel genset test setup at UW-Madison

A testbed for the diesel genset has been established at UW-Madison. The test setup consists of a commercial 10kW diesel genset connected to the UW-Microgrid system [7,20,21] and is shown in Fig. 4. The speed regulator in the genset is a mechanical governor and the exciter is a brushless unit having a single-phase output with a diode bridge rectifier to provide DC to the main field winding. A transformer is placed in series with the machine to step down the output of the machine to 208V which is the nominal voltage of the microgrid. Resistor banks are connected at the secondary of the transformer to load the machine.

The parameters of the main generator, exciter, and the voltage regulator in the genset were obtained from the manufacturer. The genset diesel engine is a four-stroke three-cylinder engine operating at rated speed of 1800 rpm. The time delay for a power stroke of this engine is calculated to be 22ms. The relationship between the fuel input and torque output of the engine was obtained from the torque-fuel map at rated speed provided by the engine manufacturer.

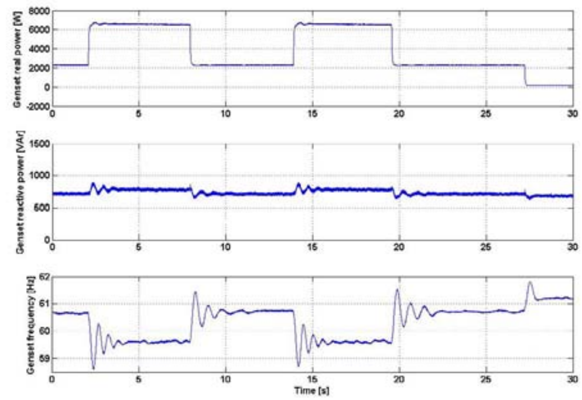

Fig. 5. Experimental waveforms for real power, reactive power output and frequency of genset for step load changes in an isolated diesel genset system.

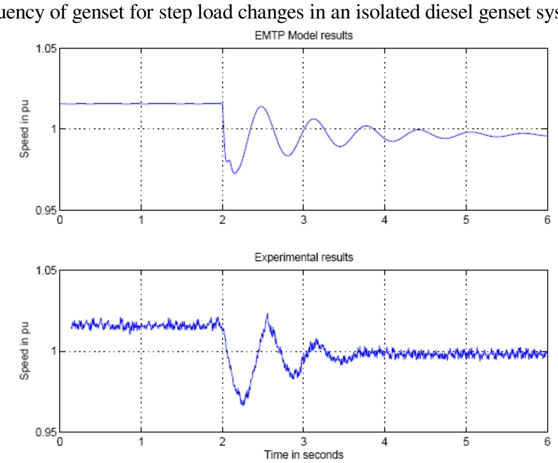

Fig. 6. Comparison of experimental results and simulated results for frequency variation for step load change in an isolated diesel genset system.

The time constants for the mechanical governor were obtained by performing step load changes. Traces for the genset real power, reactive power, and frequency for a step load change test are shown in Fig.5. For this test the output of the genset was connected to resistive load banks through a step-down transformer.

The Fig. 5 waveforms confirm that there is a change in the steady-state frequency with loading. The change in frequency is consistent with the manufacturer-specified droop value of 5%. The second-order dynamics of the mechanical governor are visible in the speed waveform.

The model for the genset was developed in the EMTP [22] simulation platform. Using the known and deduced parameters for the genset, the step load test was performed via simulation. The results obtained from the simulation compare well with the test results and are shown in Fig.6.

IV. Test Results for Conventional Genset Operation in a Microgrid Power System

The operation of the genset in the presence and absence of inverter-based sources in the microgrid was studied by performing experimental as well as simulation tests. The experimental test results are reported in this paper. The objective of the tests is to evaluate the performance of the diesel genset in a microgrid system without modifying its controls. The load sharing capability of the sources in the system can be observed during islanding and subsequent load changes and the system frequency has been monitored.

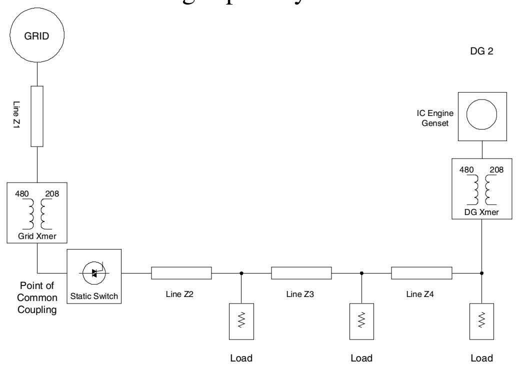

Fig. 7. One-line diagram of UW Microgrid power system with a synchronous source connected to grid.

A. Experimental results for genset and grid in microgrid

Figure 7 shows the test setup for studying the interaction between the genset and the grid. The various events taking place during the test are:

1. At t=0, the genset (DG2) and the grid are connected and are supplying the load.
2. At t=3 sec, the load in the system is increased.
3. At t=10.2 sec, the grid is disconnected.
4. At t=17.4 sec, the load in the system is decreased.

Figure 8 shows the active and reactive power outputs of the grid and the genset during the test. It is apparent that there is a significant amount of circulating reactive power between the two sources while the grid and genset are connected together until t=10.2 sec. The genset is regulating its terminal voltage to a fixed value which is the cause of the circulating VARs. Ideally, the terminal voltage would be determined by performing a power flow, but each source has no knowledge of the system load in a microgrid system. In the absence of any communications, it is not possible to perform a power flow analysis in real time.

At t=3 sec, the load in the system is increased and this extra load is picked up by the grid since it is a stiffer source, forcing the genset to operate at fixed frequency and, hence, fixed output power. The reactive power output of each source also varies as the voltages in the system are changed due to the increase in load.

At t=10.2 sec, the genset is forced to pick up the entire system load when the microgrid is disconnected from the grid. The frequency of the genset drops and its waveform (Fig. 9) shows oscillations due to the second-order response of the mechanical governor. These oscillations also appear in the microgrid voltage and, hence, in the output real and reactive power as shown in Fig. 8.

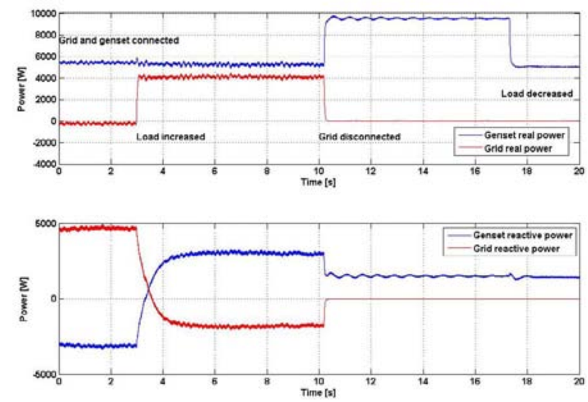

Fig. 8. Experimental waveforms for real and reactive power output for grid and genset operation in a microgrid power system.

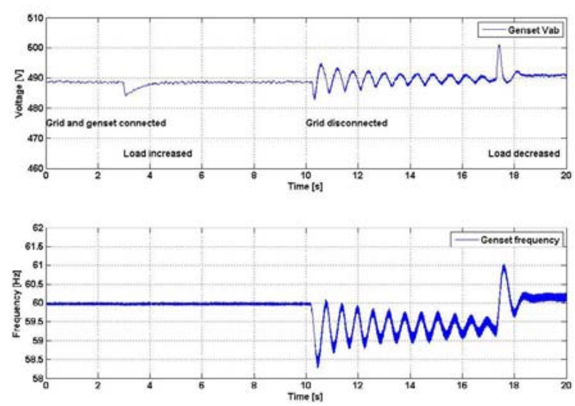

Fig. 9. Experimental waveforms for genset terminal voltage and system frequency for grid and genset operation in a microgrid power system.

B. Experimental results for genset, inverter based microsource and grid in Microgrid

Fig. 10 shows the test setup for studying the interaction between the genset (DG2), inverter based source (DG1) and the grid. The key events taking place during the experimental test include:

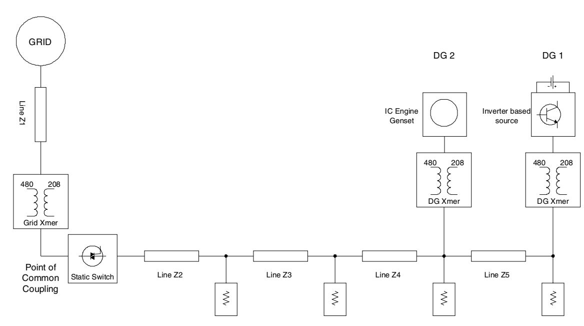

Fig. 10. One-line diagram of Microgrid power system with a synchronous genset source and a power electronic inverter based source.

1. At t=0, the genset (DG2) and the grid are connected and are supplying the load.
2. At t=2 sec, the grid is disconnected.
3. At t=7.5sec, the load in the system is increased

The inverter-based source has a droop of 0.5Hz over its entire range of operation from no load to full load. In constrast, the genset with the conventional controller has a droop of 3Hz (i.e., 5%) from no load to full load. Figure 11

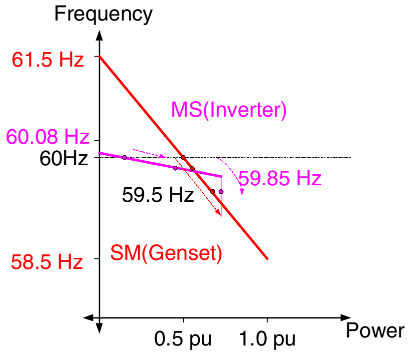

Fig. 11. Droop curves for inverter based source and genset with conventional controller.

shows the power-frequency curves for both sources. For any change in load, the output power of the genset will vary by a very small amount and the inverter-based source will track the load. Once the inverter based source hits its output limit (minimum or maximum) the genset output will change to track the load. The experimental tests were carried out such that once the grid is disconnected at step 3 the increase in load will be picked up by the inverter based source. The second increase in load (step 3) pushes the inverter based source to its limit and forces the genset to pick up some of the excess.

Fig. 12 shows the active and reactive power outputs of the grid and the genset during the test. We can see that when the grid and genset are connected together from start to 2 sec there is a significant amount of circulating reactive power between the grid and the genset. As mentioned before the genset is regulating its terminal voltage to a fixed value which is the cause of the circulating VAR.

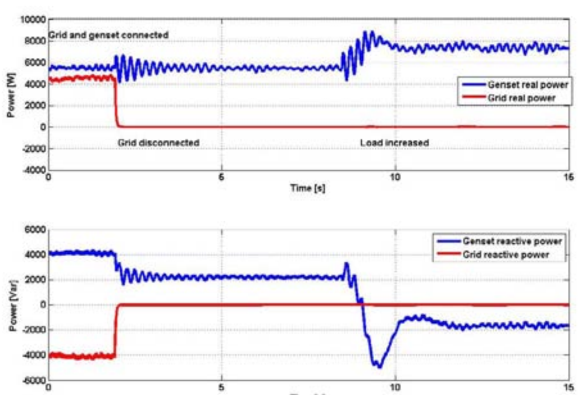

Fig. 12. Experimental waveforms for real and reactive power output for grid and genset operation in a microgrid power system with inverter based source.

At this point in time the microgrid system is importing power from the grid (Fig. 12) and is operating at grid frequency (Fig. 13). When the grid is disconnected the sources in the microgrid have to pick up the excess load. From Fig. 12 we can see that the genset output power increased by a small amount (Fig. 12) in comparison to the output of the inverter (Fig. 14). At 7.5s the increase in load pushes the inverter based source to its limit, this causes the genset to increase its output power and control frequency. The inverter based source has an overload capability that allows it to meet the demand until the genset output power increases and this takes roughly 3 sec (Fig. 12). The system frequency in steady state is close to 59.5Hz which is lesser than the minimum permissible limit of 59.75Hz in a microgrid application [3].

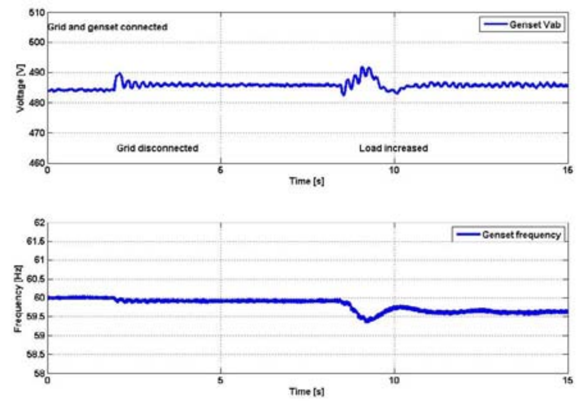

Fig. 13. Experimental waveforms for genset terminal voltage and system frequency for grid, inverter based source and genset operation in a microgrid power system.

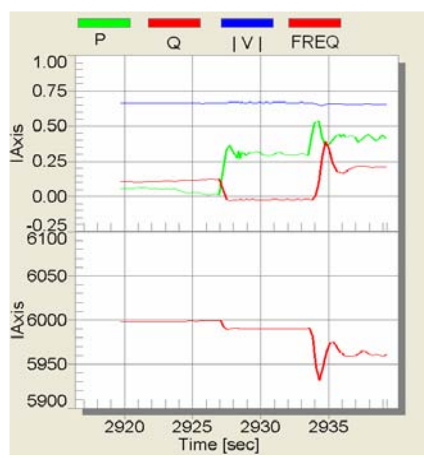

Fig. 14. Experimental waveforms for inverter real and reactive power output and terminal voltage and frequency (frequency*100) in a microgrid power system with genset based source and grid. Power base is 16kW and voltage base is 740V

C. Summary of conventional genset operation in a Microgrid power system

From the various experimental tests performed with the genset, inverter based microsource and grid we have seen that the system is stable during islanding events. However the absence of QV droop on the genset voltage controls causes large circulating VAR's to flow in the system. After islanding multiple units will share power according to their power frequency droop curves. As the genset droop is more than the droop of the inverter sources the power variation in the system will be picked up by the inverter based source. Once the inverter based sources hit their power limit the frequency in the system will be governed by the genset. During this time the dynamics of the mechanical governor will result in oscillations of the speed of the genset and hence in the frequency of the system. Furthermore as the voltage regulator in the genset does not incorporate the speed command in its control the oscillations in speed will be transferred onto the terminal voltage. This can only be eliminated by designing new control schemes for the genset.

V. Genset Modifications for Operation in a Microgrid Power System

To operate the diesel genset in microgrid environment modifications in the governor control and voltage regulator control need to be made. The modified controller for the genset has been designed using state feedback techniques. The first step in this process is to design an observer (Fig. 15) that would estimate the state of the system. An operating model for the genset has been developed from the state equations of the system. The machine model developed for the synchronous machine depends on the knowledge of the rotor position for achieving the rotor reference frame transformation. A rotor angle observer has been developed from the measured rotor position which enables us to estimate the speed accurately and convert the stator terminal quantities into the synchronous reference frame located on the rotor of the machine. In the wound field machine the d-axis field voltage is the only control handle that we have to change the terminal voltage. This field voltage controls the mutual d-axis flux linkage that governs the output q-axis terminal voltage. Hence to control the output voltage we need to accurately estimate the d-axis flux linkages. A closed loop observer for the machine state equations has been developed for this purpose.

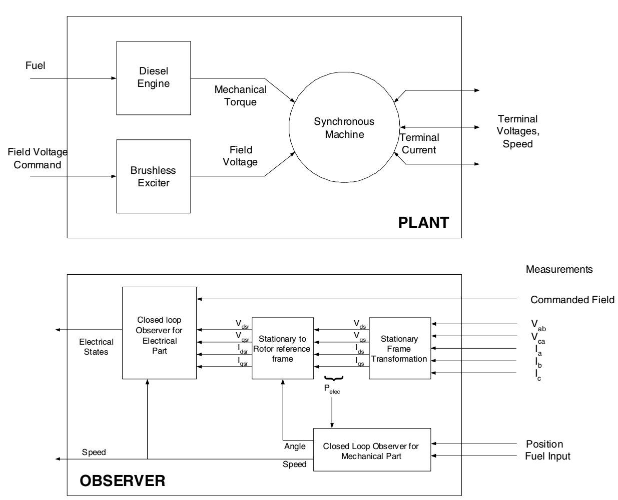

Fig. 15. Observer structure for genset.

The reference commands for the speed and terminal voltage for the genset are obtained from the real power – frequency droop and reactive power-terminal voltage droop curves. The desired terminal voltage and speed is then passed on as commands to the speed controller and voltage regulator (Fig. 16). The mechanical governor is replaced by an electronic actuator that utilizes a PWM command to vary the fuel input to the engine. The speed controller output is a PWM signal with a variable duty ratio. The voltage regulator controls the output of the brushless exciter by varying the input current of the exciter machine. The regulator controls the input current of the exciter machine and decouples it from the speed of the machine.

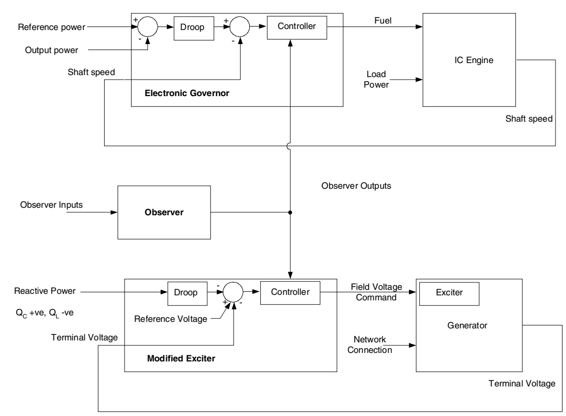

Fig. 16. Proposed controller structure for genset

VI. Simulation Results for Modified Genset Controller Operation

The section presents the simulation results with the modified genset controller operating in the same test conditions as in section IV. The first sub-section presents the results for the genset operating in a microgrid that has no inverter based source. The second sub-section presents simulation results with the genset operating in the microgrid that has inverter based sources.

A. Simulation results for modified genset and grid in Microgrid

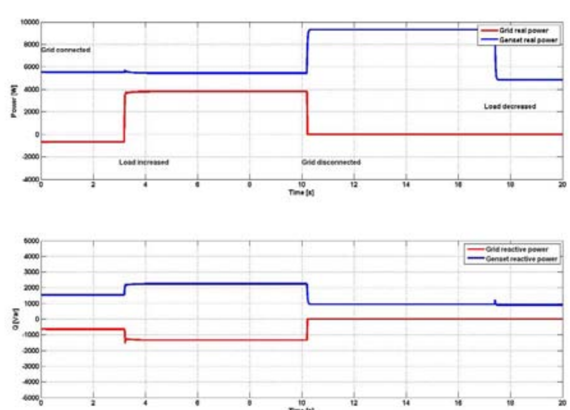

Fig. 17. Simulation waveforms for real and reactive power output for grid and modified genset operation in a microgrid power system

The various events taking place in the simulation are listed below:

1. At start the genset (DG2) and the grid are connected and are supplying the load.
2. At 3 sec the load in the system is increased.
3. At 10.2 sec the grid is disconnected.
4. At 17.4 sec the load in the system is decreased.

Prior to islanding we can see that the circulating VAR's have been decreased to 1500VAr (Fig.17) from 4800VAr (Fig.8) due to the presence of the reactive power droop curves which changes terminal voltage Fig.18. The speed of the genset (Fig. 18) is restored to its steady state value within a second with very good dynamics in comparison to the 3-5s response seen with the mechanical governor. The initial change in speed (Fig. 18) is due to the time delay engine which prevents the speed controller from restoring the frequency instantaneously.

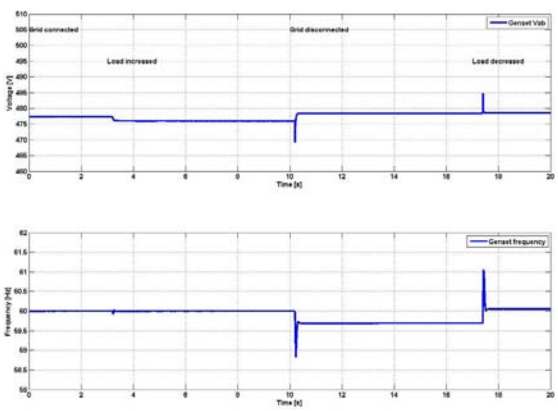

Fig.18. Simulation waveforms for genset terminal voltage and system frequency for grid and modified genset operation in a microgrid power system

B. Simulation results for modified genset, inverter based source and grid in Microgrid

Fig. 19 shows the steady state points in the power frequency plane; the various events taking place are:

1. Island from grid at 2s
2. Increase in load at 7.5s

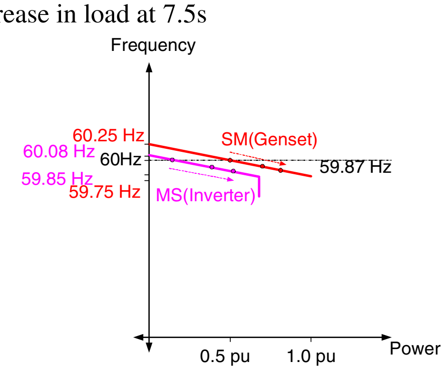

Fig. 19. Droop curves for inverter and genset with modified controller

Fig. 20and Fig. 21 gives the various results obtained from the simulation. One of the chief problems with the existing genset voltage regulator was the large circulating VAR's due to the absence of a reactive power droop. From Fig. 20 we can see that the circulating VAR's have been significantly brought down. After the islanding and subsequent load change events the system is stable and the frequency and voltage are within prescribed [3] limits. Due to the electronic governor the speed of the genset reaches its steady state value (Fig. 21) within a second. As the power output of the genset responds quickly the period of the transient overshoot in power (Fig. 20) for the microsource is also decreased from 3s (Fig. 12) to less than 1s.

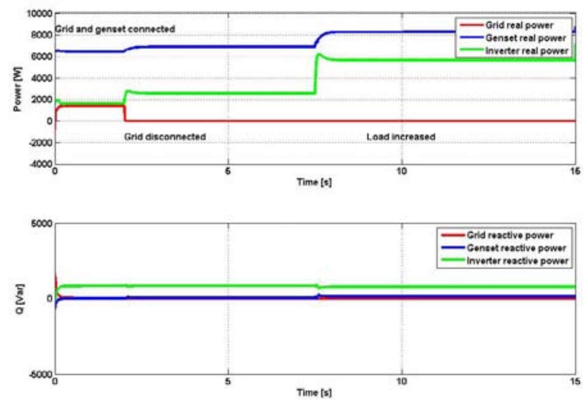

Fig. 20. Simulation waveforms for real and reactive power output for grid, inverter and genset for operation in a microgrid power system with inverter based source and modified genset

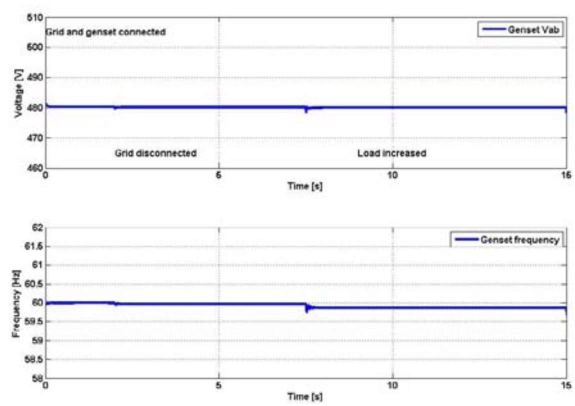

Fig. 21. Simulation waveforms for genset terminal voltage and frequency for grid, inverter and modified genset operation in a microgrid power system

VII. Conclusions

The paper discusses the modeling and control issues related to such gensets for their operation in a distribution system that contains multiple DG's including inverter-based sources. From the various experimental tests performed with the genset, inverter based microsource and grid we have seen that the the absence of QV droop on the genset voltage controls causes large circulating VAR's to flow in the system. As the genset droop is more than the droop of the inverter sources the power variation in the system will be picked up by the inverter based sources. Once the inverter based sources hit their power limit the frequency in the system will be governed by the genset. During this time the dynamics of the mechanical governor of the genset will result in oscillations in its speed and hence in the frequency of the system. The paper proposes a new genset controller for alleviating these issues and enabling the various sources to share power and maintain power quality within the system. The operation of the new controller is demonstrated using simulation results. As part of future work the operation of the modified genset controller will be verified experimentally.

VIII. Acknowledgment

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